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Evaluation of Soil Physical Quality Index *S* for Some Tropical and Temperate Medium-Textured Soils

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ABSTRACT

The soil physical quality (SPQ) index *S* can provide inconsistent designations of SPQ and has a lack of consistency with other physical indicators for some soils. The aim of this study was to compare the suitability of *S* in identifying SPQ against 12 SPQ indicators, including water-release-related indicators, physical properties, and visual examinations. This study was conducted on medium-textured soil samples taken from tropical and temperate soils. Comparisons of SPQ class and relationships between indicators were used to judge the *S* SPQ designation. For the studied soils, *S* classified SPQ in the same way as other indicators when the condition of the soil was optimal or degraded but not when it was intermediate. This demonstrates that the proposed critical limits for *S* are not generally valid and do not apply for all soil conditions. Porosity parameters from the water release curve were more consistent indicators of SPQ than *S*. Our work also demonstrates that scores from visual examinations have at least similar resolution ($P > 0.05$) to the other indicators of SPQ evaluated. The use of *S* as an indicator to be considered as part of a minimum data set of indicators of SPQ assessment is less viable when other indicators such as bulk density, porosity, and visual examination are much more easily determined and more consistent than *S*. Therefore, it is too ambitious to consider that a unique indicator such as the *S* index could be used to evaluate SPQ as such.

Abbreviations: AC, air capacity; BD, bulk density; PAWC, plant-available water capacity; RWC, relative water capacity; SOC, soil organic carbon; SPQ, soil physical quality; SS-VSA, soil structure using the visual soil assessment protocol; StI, structural stability index; SWRC, soil water release curve; Tyagg, type of aggregates index; VESS, visual evaluation of soil structure; VSA, visual soil assessment; WSA, water-stable aggregates.

The *S* index of soil physical quality (SPQ) is defined as the slope of the soil water release curve (SWRC) on a mass base at its inflection point on a logarithmic matric potential scale. The use of the *S* index proposed by Dexter (2004a) as an “easy and unambiguous measure” was based on the idea of integrating observations of a range of soil properties to obtain an overall assessment of SPQ.

The suitability of *S* in the diagnosis of SPQ has been studied by several researchers. For instance, Dexter (2004a, 2004b, 2004c) suggested that *S* correlates with several important soil physical properties, which was supported by the ability of the van Genuchten (1980) equation to integrate over the whole SWRC and the corresponding pore size distribution (Dexter et al., 2008). Dexter (2004a) stated that in the SWRC, the pores that are smaller than those corresponding with the inflection point represent textural pores, while pores larger than those corresponding with this point are mainly structural pores. The use of *S* as an indicator of SPQ is based on soil physical degradation being always related to an alteration in the structural pore distribution, which leads to a change in the shape of the SWRC and consequently to a change in the *S* value.

Dexter and Czyż (2007) stressed that there are two additional aspects supporting *S* as an adequate SPQ index. First, “the same values of *S* have the same physical meaning in widely different soils, this is not the case with other soil physical properties, such as bulk density” (BD). Second, *S* provides a more objective measurement with higher resolution (low coefficient of variation and standard error) than other measures such as subjective visual examination of the SPQ in the field.

Nonetheless, in the literature there are very well-established critical values of BD for root growth developed for different soil textures, which enable evaluation of the physical condition of soils. With respect to the second assumption, comparisons of the SPQ evaluation using visual examination methods and *S* have not yet been reported in the literature.

Another factor relevant to this discussion is the value of $S = 0.035$ proposed by Dexter (2004a) as a boundary value of soil degradation problems. This arbitrary value was established according to the experience of the author with temperate soils ranging in clay content from 4 to 73% and based on relationships between *S* and other critical limits of different soil physical properties. Dexter and Birkas (2004) and Tormena et al. (2008) maintained that a value of $S = 0.035$ enables identification of variations in the soil physical condition among different soils. On the other hand, de Jong van Lier (2012, 2014) mentioned that *S* values at an order of magnitude higher than those described by Dexter (2004a) have been reported, as well as inconsistency in the use of *S* as an absolute indicator of SPQ.

Finally, it is important to stress that although Dexter (2004b) mentioned that “nearly every soil laboratory has the equipment necessary to determine the SWRC” and that the determination of soil properties related to soil structure are “extremely costly in both time and money”, there are many studies in the literature showing contrary arguments. For instance, Minasny and Hartemink (2011) pointed out that information on soil water retention is usually missing in soil databases, especially for tropical soils, because the direct method to determine the SWRC is tedious and expensive in time and money. Therefore, several efforts have been dedicated to estimating the SWRC from easily accessible soil properties using pedotransfer functions (Nguyen et al., 2014; Botula et al., 2013).

Although there is an acceptance of the *S* index in SPQ evaluations by some researchers, in this study some constraints on its use are identified. The aim of this study was to compare the suitability of *S* in identifying the SPQ condition of different tropical and temperate soils against the more frequently used soil physical and hydraulic properties on the one hand and visual examination methods on the other.

MATERIALS AND METHODS

Study Area and Soil Data Set

The study was based on medium-textured soil samples taken from nine sites, with five located in a tropical environment (north-central part of Venezuela, V2–V6) and four in a temperate one (Flanders region of Belgium, B1–B4). The sites selected differ in those factors that affect soil quality such as soil type, soil management, land use, and vegetation type (Table 1). This provided a wide range of SPQ, which enabled testing of the different indicators that were selected for this study. In the north-central part of Venezuela and the Flanders region of Belgium, six locations were sampled in triplicate per soil.

Methods and Analysis

S Index Calculation and Parameter Estimation

Undisturbed samples were randomly collected in 100-cm^3 Kopecky rings (5-cm diameter by 5 cm long) centered at a depth of 10 cm. The SWRC data were determined from the wet to the dry range at eight different matric potentials: −1, −3, −5, −7, −10, −33, −100, and −1500 kPa. The procedure followed was described by Cornelis et al. (2005). Briefly, after determining water contents at pressures between −1 and −10 kPa using sand boxes (Eijkelkamp Agrisearch Equipment), the samples were further divided into undisturbed subsamples using sharpened steel 20-cm^3 cylinders and into disturbed subsamples. The undisturbed subsamples were used to determine the water content at −33 kPa and the remainder of the disturbed subsamples for water content determination at −100 and −1500 kPa using pressure chambers (Soilmoisture Equipment). The coupled matric potential–water content pairs represent single measurements on single samples.

The *S* index (Dexter, 2004a) was calculated by fitting the soil water retention data to the mathematical model of van Genuchten (1980) with the $m = 1 - 1/n$ constraint to the observed SWRC:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m} \quad [1]$$

where θ_s is the gravimetric soil water content at saturation (kg kg^{-1}); θ_r is the residual gravimetric soil water content (kg kg^{-1}); *h* is the water suction (equal to the modulus of the matric potential, cm); and α (cm^{-1}) as well as the dimensionless *n* and *m* are parameters are related to *h* and the curve's slope at its inflection point, respectively.

After the parameters of the van Genuchten (1980) function were determined by fitting Eq. [1] to the SWRC data, the slope at the inflection point, *S*, was calculated (Dexter, 2004a):

$$S = \frac{\mathrm{d}(\theta_i)}{\mathrm{d}(\ln h_i)} = -n(\theta_s - \theta_r)\left(\frac{2n-1}{n-1}\right)^{(1/n)-2} \quad [2]$$

where θ_i and h_i are the water content and the water suction modulus of the water potential at the inflection point:

$$\theta_i = (\theta_s - \theta_r)\left(1 + \frac{1}{m}\right)^{-m} + \theta_r \quad [3]$$

$$h_i = \frac{1}{\alpha}\left(\frac{1}{m}\right)^{1/n} \quad [4]$$

Although *S* is always negative, the modulus of *S* is presented and discussed in this study.

Because the *S* index depends on θ_r, it was necessary to set θ_r in Eq. [1] and [2] to zero to prevent negative fitted values being obtained (Dexter et al., 2008; Cornelis et al., 2005; Dexter, 2004b) and thereby allowing better comparison among the various soils. The estimation of the parameters θ_s, α, and *n* was performed in the MatLab 8_1 environment (The MathWorks).

Soil Physical Quality Indicators

To compare the suitability of *S* in identifying SPQ, its designation was compared against 12 SPQ indicators, including water-release-related indicators, physical properties, and visual examinations. Previous studies (Pulido Moncada et al., 2014a, 2014b) demonstrated the usefulness of the selected indicators of SPQ as part of a minimum data set of indicators.

Physical Soil Properties

Undisturbed samples were also used to determine BD, saturated hydraulic conductivity (K_s), air capacity (AC), plant available water capacity (PAWC), and relative water capacity (RWC). The value of K_s was determined using the constant-head method with a closed laboratory permeameter system (Eijkelkamp Agrisearch Equipment). Soil physical properties such as AC ($\theta_{\psi=0kPa} - \theta_{\psi=-33kPa}$), PAWC ($\theta_{\psi=-33kPa} - \theta_{\psi=-1500kPa}$), and RWC ($\theta_{\psi=-33kPa}/\theta_{\psi=0kPa}$) were calculated from the SWRC data, with ψ denoting matric potential.

The pore volume distribution function was evaluated as suggested by Reynolds et al. (2009), hence the "normalized" pore volume distribution function, $S^*(h)$ (dimensionaless), was determined by plotting the slope of the SWRC expressed as the volumetric water content, θ_v (m^3 m^{-3}), vs. ln(h), against equivalent pore diameter, d_e (μm), on a $\log_{10}$ scale:

$$S^*(h) = \frac{S_v(h)}{S_{vi}} \quad [6]$$

$$d_e = \frac{2980}{h} \quad [7]$$

where $S_v(h)$ is the slope of the $\theta(h)$ vs. ln(h) function, and S_{vi} is the slope at the inflection point of the SWRC. Details on the derivation of Eq. [6] and [7] were given by Reynolds et al. (2009). Equation [7] is the capillary rise equation.

The pore volume distribution was also characterized and compared using location and shape parameters (Blott and Pye, 2001), where the location parameters included the mode, median, and mean d_e values and shape parameters included skewness (asymmetry) and kurtosis (peakedness) (Reynolds et al., 2009, Eq. [13–19]). The median d_e (d_{median}) occurs at a degree of saturation of 0.5, and the modal d_e (d_{mode}) corresponds to the relative water content or matric potential at the SWRC inflection. The d_{mode} also defines the most frequently occurring d_e value in the pore volume distribution.

Additionally, disturbed samples were collected simultaneously with undisturbed samples. These samples were used for determining other SPQ properties: (i) the percentage of water-stable aggregates (WSA) using the wet-sieving test of Yoder modified by Kemper and Rosenau (1986); (ii) the particle size distribution by sedimentation using the pipette method (Gee and Or, 2002); and (iii) soil organic C (SOC) by wet oxidation (Walkley and Black, 1934).

The structural stability index (StI) suggested by Pieri (1992), which expresses the risk of soil structural degradation associated with SOC depletion, was also calculated:

$$\mathrm{StI}(\%) = \frac{1.72 \times \mathrm{SOC}}{\mathrm{clay} + \mathrm{silt}} \times 100 \quad [8]$$

Visual Examination of Soil Structural Quality

Finally, the macrostructure, in terms of SPQ, was investigated using the overall score of the visual evaluation of soil structure (VESS) of Ball et al. (2007) and the visual soil assessment (VSA) of Shepherd (2009), in conjunction with the individual score of the soil structure using the VSA protocol (SS-VSA) and the visual type of aggregates index (Tyagg) (Pulido Moncada et al., 2014b). For this visual examination of soil structural quality, blocks of soil (20 cm deep, 10 cm thick, and 20 cm long) were taken at each sampling location.

The VESS was conducted by describing the condition of a soil block broken by hand. The visual examination consisted of identifying layers of contrasting structure and giving a score to each soil layer by comparing the appearance of the soil block (after hand breaking) with a visual key proposed by Guimarães et al. (2011). In this visual key, the attributes evaluated are the size and appearance of aggregates, visible porosity and roots, appearance after breakup, distinguishing features, as well as appearance and description of natural or reduced fragments of 1.5-cm diameter. The overall score of a soil was then determined by multiplying the score of each layer by its thickness and dividing the product by the overall depth. The blocks of soil were graded on a scale from 1 to 5 where 1 represents the best condition.

The VSA was conducted following visual assessment of the key indicators (soil texture, soil structure, soil porosity, number and color of soil mottles, soil color, earthworms, soil smell, potential rooting depth, surface ponding, surface cover, surface crusting, and soil erosion) presented on the scorecard suggested by Shepherd (2009). Each indicator used in this method was given a visual score of 0 (poor), 1 (moderate), 2 (good), or an in-between score (0.5 = moderately poor and 1.5 = moderately good). The ratings for each indicator were then weighted and summed, resulting in a final score for the soil structural quality. For the SS_VSA, the soil blocks were individually dropped three times from a height of 1 m into a plastic tray. After dropping, the soil fragments were arranged from coarse to fine fractions over a plastic bag. The aggregate- or fragment-size distribution was then compared with photographs and criteria given in the field guide (Shepherd, 2009).

To determine the visual Tyagg, aggregates of 1- to 2-cm diameter were described in terms of shape according to FAO (2006). An abundance of rounded aggregates was considered as an indicator of good quality for crop growth and an abundance of sharper edged aggregates as poor quality. The abundance of a certain type of aggregate was graded on a scale from 1 to 5, where 1 was the best (Pulido Moncada et al., 2014b).

ASSESSMENT OF SOIL PHYSICAL QUALITY

The mean of three replicates per location was used to obtain the 54 values of S, BD, AC, PAWC, RWC and K_s. These were used for comparison with the other SPQ indicators such as SOC, StI, WSA, VESS, VSA, SS_VSA, and Tyagg. The soil quality designation provided by the different SPQ indicators was compared within and among soils. The optimal ranges or critical limits of the SPQ indicators are shown in Table 2. The relationships between S and the other SPQ indicators were determined by simple regression models ($P < 0.05$). A Levene's test (Schultz, 1985) was applied to compare differences between coefficients of variation of the indicators determined with an analysis of variance ($\alpha = 0.05$), with indicators as factor, on the ratio of the absolute deviations associated with each observation from its respective group mean divided by the group mean. A post hoc Duncan test was used to detect statistical differences among indicators.

RESULTS AND DISCUSSION

Fitting Parameters Used for Estimating *S* Index

Table 3 shows details of the *S* index values together with the van Genuchten (1980) parameters used in its calculation for the different tropical and temperate soils. It should be noted that to allow comparison of the *S* index in different studies, Dexter (2004a, 2004b, 2004c) (i) expressed water content gravimetrically (kg kg^{-1}) in calculating the parameters of the van Genuchten (1980) equation, (ii) used the constraint $m = 1 - 1/n$, and (iii) set θ_r equal to zero, as was also done in our study. Although these premises should be assumed as fulfilled by researchers, studies can be found in the literature where *S* and its critical value (Dexter, 2004a) were used without full consideration of these aspects (e.g., Calonego and Rosolem, 2011; Vizitiu et al., 2011; Silva Guedes et al., 2012).

Soil Physical Quality Based on Different Indicators: Comparison of *S* Soil Physical Quality Designation

The physical quality of the soils under study was evaluated by comparing the indicator values and their given classes (Table 4). Based on the research conducted by Reynolds et al. (2009), soils were grouped by SPQ class. Soils were organized into three groups based on the SPQ classes given by the different indicators: good SPQ, moderate SPQ, and poor SPQ. A general moderate class was allocated to each site based on the predominant designation among the indicators. For instance, some of the studied soils indicate a moderate–good condition, or moderate–poor condition, or just moderate. In any case, those soils were classified as the moderate group because they do not belong to the good or poor groups.

Group 1, good SPQ, included only Soil V2. The BD, AC, PAWC, SOC, StI, K_s, WSA, VESS, VSA, SS_VSA and Tyagg classified the physical quality of the soil as good for crop production. This suggests no limitation for root growth as well as water storage and movement. Although the majority of the other SPQ indicators fell within their respective optimal ranges, RWC was out of the optimal range, being above the higher critical value (“limited aeration”). In this group, the good SPQ designation provided by the *S* index was thus consistent with the designations provided by most of the other indicators.

The soils in Group 2 (V4, V5, B1, B2, B3, and B4) were considered as having a moderate SPQ for agricultural purposes. For these soils, different ranges between good and poor were obtained for the SPQ indicators. For instance, Soil V5 had a high SOC content and WSA, but evidence of a loss of structural quality was manifested by a high BD, limited aeration (AC and RWC), limited water storage (PAWC), and poor macrostructure arrangement (VESS). The other soils of this group had evidence of quality loss in either aggregate stability (WSA) or macrostructural quality (VESS, VSA, SS_VSA, and Tyagg). The SPQ designation provided by the *S* index for these soils was not consistent with those of the majority of the other indicators (Table 4).

Group 3, poor SPQ, included V3 and V6 soils. A degraded or compacted condition was designated by a high BD, poor aeration (AC and RWC), low to medium SOC content, moderate to poor WSA, poor structural and soil quality (VESS, VSA, SS_VSA, and Tyagg), and low values of StI. The SPQ designations of the *S* index were consistent with those of the other indicators.

Comparison of the SPQ classes shown in Table 4 confirms the complexity of soil structure and the risk of evaluating SPQ based on a sole indicator. The selection or use of only one out of the several indicators shown in Table 4 represents a simpler approach and consequently could trigger inconsistent assessments. Additionally, it is also shown that the optimal ranges and critical limits of the physical properties used, including visual evaluation of macro structure, seemed consistent and applicable to a wide range of agricultural soils, differing in crop and land management, soil texture, and climate. This has been demonstrated by other researchers such as Reynolds et al. (2009), Newell-Price et al. (2013), and Pulido Moncada et al. (2014b).

For our set of soils, the critical limit of $S = 0.035$ was capable of classifying the physical quality of the soils in the same way as other SPQ indicators only when the condition of the soil was optimal or degraded but not when it was intermediate (Table 4). A moderate class provides evidence of structure dynamics during degradation or amelioration processes. Therefore, the appropriate evaluation of a moderate SPQ class is meaningful. Although the study conducted was limited, with only one soil classified as good SPQ and two soils classified as poor SPQ, the SPQ groups were considered reliable or good enough to be used to conduct the comparative analysis among the SPQ indicators.

A higher value of *S* was obtained for the good SPQ group than for the poor SPQ group. However, it must be emphasized that intermediate values of *S* were not present within the moderate SPQ group. The values of *S* within the moderate SPQ group surpassed or followed those from the other SPQ groups. Our results suggest no clear tendency for high values of *S* to relate to a good soil condition for crop production or for low values of *S* to correspond to limiting conditions (Table 4).

The value of $S = 0.035$ has been questioned by de Jong van Lier (2014) and Reynolds et al. (2009) because of its inconsistent designations of SPQ and a lack of consistency with other physical indicators. Consequently, the critical limit proposed by Dexter (2004a) as a discriminating threshold of soil degradation problems does not appear to be applicable for all types of soil or under all conditions of management and should be used judiciously and in relation to other indicators for assessing SPQ.

Soil Physical Quality Estimation Based on the *S* Critical Value

To further evaluate the use of the critical limit $S = 0.035$, simple regressions of *S* on other individual SPQ variables from our data set (Table 5) were then used to predict *S* at the optimal range or critical limit of each SPQ variable. This prediction was used as a tool to discover differences in optimal ranges or critical limits of the *S* index compared with that proposed by Dexter (2004a).

Statistical relationships between *S* and other SWRC-related indicators must be seen within the limitations of interdependency between the variables. Therefore, in contrast to Dexter (2004a) and Dexter and Czyż (2007), the regression equations were calculated just to find any tendency of relationship between variables but not for developing estimation equations. The results showed significant relationships with low coefficients of determination (R^2) (Table 5). This can be attributed to the large and wide range of the data set and to the existence of nonlinear relations between the variables.

The critical limits of *S* obtained by the equations shown in Table 5 differ with the type of predictor variable. It varies within a range of 0.047 to 0.038 for the good SPQ class and 0.040 to 0.029 for the poor SPQ class. In any case, the criterion of a boundary value of $S = 0.035$ is not generally valid and does not apply for the soils in our study.

Andrade and Stone (2009) found that for their Brazilian Cerrado soils, a critical value of $S = 0.045$ was adequate to separate soils of good structure from soils with a tendency for degradation, while values of $S < 0.025$ corresponded to physically degraded soils. Using the critical values suggested by Andrade and Stone (2009), Cunha et al. (2011) found that *S* was well correlated to other soil physical properties and enabled evaluation of the SPQ of tropical soils under different soil tillage systems and cover crops.

Aparicio and Costa (2007) found that, for Argentinean Pampas soils, values of *S* ranged between 0.60 and 0.82, which surpasses the threshold value of $S = 0.035$. Although *S* was only correlated with BD, total porosity, and penetration resistance, it was included as a predictor variable for estimating the number of years of continuous cropping of Argentinean Pampas soils (a measure related to soil quality). Aparicio and Costa (2007) supported the use of *S* as a good indicator of soil quality based on the selection made by the statistical model. However, the very high values of *S* (which could imply values of parameters such as *n* out of normal range), and the lack of a correlation between *S* and other indicators within different soil layers, are aspects that were overlooked when selecting *S* as a predictor variable (e.g., indicators) to be included in their model.

Similarly, in low-lying agricultural peat soils in England, where *S* values range between 0.22 and 1.03, lower values of *S* were considered to correspond to a loss of structural pores and degradation in soil structure (Kechavarzi et al., 2010). On the contrary, according to de Jong van Lier (2012), high values of *S* have been found in degraded soils and low values of *S* without apparent association with soil productivity. He stated that the *S* index does not have a generally applicable critical value for a wider range of soils, and its use should be limited to comparisons of different tillage and management practices in a soil. Additionally, relationships found between the *S* index and porosity are explained by the fact that in agricultural soils, macropores are destroyed (de Jong van Lier, 2014). He also emphasized that variation in θ_s affects proportionally the value of *S*. Therefore, the correlations found between *S* and porosity "may be considered as a mere reflection of this mathematical fact."

From the relations between *S* and the other indicators found for the studied medium-textured soils, we suggest that a range of *S* values could be established for each soil type (textural class) instead of a unique value. This is supported by Garg et al. (2009), who stated that the value of *S* decreases as the texture coarsens. They found that for Indian soils (6–81% clay), *S* decreased with an increase in the average clay content up to 20 to 30%, after which *S* started increasing steadily, and then decreased drastically when the average clay content exceeded 45%. In fact, Pulido Moncada et al. (2014a) found that 33% was the optimal level of clay content beyond which soil structural quality decreases.

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The *S* Index as a Boundary between Textural and Structural Porosity

Figure 1 shows the mean of the pore volume distributions and SWRC of the soils grouped as good SPQ, moderate SPQ, and poor SPQ.

The curve of the good SPQ group was used as the optimal pore volume distribution. The mean curve of the moderate SPQ group had a normalized pore-volume distribution, with greater densities of smaller pores and smaller densities of larger pores than the good SPQ group. Its SWRC showed greater degrees of saturation than the good SPQ group. This relates to a poorer SPQ than the good SPQ group.

The poor SPQ group had a lower density of smaller pores than the moderate SPQ group, whereas the opposite was true compared with the good SPQ group. The lowest density of large pores was present in this group of soils. The SWRC showed higher degrees of saturation for the poor SPQ group than for the other groups. This water storage excess corresponds with a very low proportion of large pores relative to soils in the good SPQ group.

The skewness and kurtosis values of the moderate SPQ (−0.34 to −0.42 and 1.14–1.16, respectively) and poor SPQ (−0.39 to −0.44 and 1.15–1.12, respectively) groups were similar to those of the good SPQ group (−0.41 and 1.14, respectively) (Table 6).This corresponds with the results of Reynolds et al. (2009), who mentioned that evidently the loss of aeration capacity and structural quality affects the location parameters of the pore volume distributions much more than the shape parameters. The d_{mode}, d_{mean}, and d_{median} of the good SPQ group were greater than the mean values of the other groups. The d_{mode} value (125.6 μm) was consistent with the optimal d_{mode} range of 60 to 140 μm proposed by Reynolds et al. (2009) for soils grouped as good SPQ. These location parameters of the SWRC are therefore better indicators of the SPQ present in the soils under study than shape parameters such as skewness and kurtosis.

The description of the pore volume distribution and the relative location of the SWRCs confirm the grouping of the soils, for assessing SPQ, based on the water-release-related indicators, physical properties, and visual examinations (Table 4). Porosity parameters are therefore more consistent indicators of SPQ than *S* for our tropical and temperate soils. In any case, if the SPQ is evaluated through the porosity status of the soil, *S* has no additional value over total porosity, which is easier to determine than *S* (de Jong van Lier, 2014).

Distribution of the small (textural) and large (structural) pores was evident from the pore volume distribution curve. According to *S* theory, the boundary between these pore sizes can be established at the inflection point. As an illustration, Table 7 summarizes the water content and matric potential at the inflection point and their respective equivalent pore diameters.

The inflection point of the SWRC for the good SPQ group occurs at 0.31 kg kg^{-1} of water content with h = −24 cm. For those soils with evidence of loss of structural quality (moderate SPQ and poor SPQ groups), the inflection point is in the range of 0.18 to 0.27 kg kg^{-1} with h between −95 to −346 cm, with most values closer to field capacity except for the sandy loam soil (B1).

The equivalent pore diameter at the inflection point of the SWRC was considerably higher for good SPQ soils (126.44 μm) than for the moderate SPQ (7–32 μm) and poor SPQ soils (10–18 μm). Those soils showing deterioration of their physical quality had a very low range of 7- to 31-μm equivalent pore diameter at the inflection point.

In the literature, the diameter size at the boundary between textural (or matrix) and structural porosity has been proposed as 50 μm (Lal and Shukla, 2004; Pagliai and Vignozzi, 2002). Our results show that at the inflection point, an overlapping of the textural and structural pores exists. For instance, for the clay loam soil (good SPQ) and the silty clay and loam soils (poor SPQ), the d_i was 126.44 and 10.97 μm, respectively (Table 7). Hence, according to Dexter (2004a), pores larger than these values correspond to structural porosity, whereas lower values are textural pores.

The boundary of textural and structural porosity is therefore difficult to delineate by parameters at the inflection point of the SWRC. Reynolds et al. (2009) argued that “if the two distributions do indeed overlap, then $h = h_i$ in *S*-theory does not demark an actual or literal boundary between structure pores and matrix pores but only a notional boundary.” In fact, a boundary between textural and structural porosity is an arbitrary concept because there is no specific value of matric potential or diameter distinguishing between these two types of pores.

Visual Examination and *S* Index Resolution

Visual examination of soil quality is a subjective assessment according to some soil scientists, but is it more objective to estimate the quality of a soil based on a single value or index derived from the SWRC of a small volume?

To assess the objectivity of the SPQ indicators evaluated in this study (in terms of their resolution), a comparison of their coefficients of variation (CVs) was conducted. Values of the CVs (Table 8) for SWRC-related indicators, soil physical properties, and scores from visual examinations were similar ($P > 0.05$), except for K_s.

This suggests that SPQ can be evaluated by both quantitative and semiquantitative indicators with a similar proportion of variation accounted for. Although soil physical indicators, including the *S* index and visual examination methods, differ in the scale of study (size of the samples), the visual examination methods were able to detect the differences in physical condition among soils similar to other physical indicators. In this study, a wide range of size scales was involved from a few micrometers to several centimeters, for instance, from <2-mm sieved and disturbed samples (SOC and StI), 1- to 2-mm aggregates (WSA), 10- to 20-mm aggregates (Tyagg), 100-cm^3 soil cores (K_s, PAWC, AC, RWC, and BD), to 20- by 10- by 20-cm soil blocks (VESS and VSA). The *S* index was determined from 100-cm^3 soil sample data and was related to the volume, continuity, and size of a pore space ranging from 7 to 126 μm (at the inflection point of the SWRC).

The influence of scale in soil structure assessment is very well known (Besson et al., 2013; Dexter, 1988). Therefore, with the purpose of evaluating soil quality in terms of soil structure status, an integration of *S* with other indicators at different scales can be established, for instance, soil quality assessed by comparison of both SWRC-related indicators and visual examination on the same soil.

De Jong van Lier (2014) emphasized that soil quality is an expression of the complexity of the system (here the soil) and that the use of a simple single indicator such as the *S* index should be viewed with great caution and skepticism, mainly because “as an absolute indicator, the value of *S* alone has proven to be incapable of predicting SPQ.”

Conclusions about the sensitivity of the indicators of SPQ compared in this study cannot be drawn from our data set because of the differences in factors such as soil type, climate, vand egetation that affect soil structural quality, as well as their possible interactions. Ideally, a comparison of the sensitivity of the indicators should be conducted by monitoring changes in SPQ with land use or soil management. Nevertheless, one of the limitations of the visual examination methods is that the scoring factor, which covers a wide range, might limit sensitivity to changes in soil quality, whereas other more continuous parameters such as SWRC-related indicators (soil porosity, BD, and PAWC) may it be more sensitive temporally or spatially.

Finally, visual examinations of SPQ are methods that summarize in a single score the evaluation of several visible and tactile features (such as the macroporosity, size, shape, and rupture resistance of aggregates, root limitations, proportion of clods, and soil color) involved in characterizing one of the most complex properties of the soil, the soil structure. These methods have proved capable for evaluating changes in structure dynamics and therefore related to soil physical properties and provide straightforward and reliable measurements of the SPQ (Pulido Moncada et al., 2014b; Boizard et al., 2013; Mueller et al., 2013).

CONCLUSIONS

Although this research was conducted with a limited data set of medium-textured soils, the lack of similarity between the *S* index and the other indicators used in classifying the SPQ demonstrates that the proposed critical limits for *S* are not generally valid and do not apply for all soil conditions. This study also demonstrated that the visual examinations have at least similar resolution to the other indicators of SPQ evaluated in the studied group of soils. Additionally, the use of *S* as an indicator to be considered as part of a minimum data set of indicators of SPQ assessment is less viable when other indicators such as BD, porosity, VSA, and Tyagg are much more easily determined and more consistent than *S*. Therefore, it is too ambitious to consider that a unique indicator such as the *S* index could be used to evaluate SPQ as such. Research efforts should be focused on the evaluation of soil quality, as a key factor of land degradation assessment, from a more complex point of view or in a more integrated approach.

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REFERENCES

Andrade, R.S., and L.F. Stone. 2009. S index as an indicator of physical quality of Brazilian Cerrado soils. (In Portuguese, with English abstract.) Rev. Bras. Eng. Agric. Ambiental 13:382–388. doi:10.1590/S1415-43662009000400003

Aparicio, V., and J.L. Costa. 2007. Soil quality indicators under continuous cropping systems in the Argentinean Pampas. Soil Tillage Res. 96:155–165. doi:10.1016/j.still.2007.05.006

Ball, B.C., T. Batey, and L.J. Munkholm. 2007. Field assessment of soil structural quality: A development of the Peerlkamp test. Soil Use Manage. 23:329–337. doi:10.1111/j.1475-2743.2007.00102.x

Besson, A., M. Séger, G. Giot, and I. Cousin. 2013. Identifying the characteristic scales of soil structural recovery after compaction from three in-field methods of monitoring. Geoderma 204–205:130–139. doi:10.1016/j.geoderma.2013.04.010

Blott, S.J., and K. Pye. 2001. Gradistat: A grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf. Processes Landforms 26:1237–1248. doi:10.1002/esp.261

Boizard, H., S.W. Yoon, J. Leonard, S. Lheureux, I. Cousin, J. Roger-Estrade, and G. Richard. 2013. Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced tillage. Soil Tillage Res. 127:34–44. doi:10.1016/j.still.2012.04.007

Botula, Y.-D., A. Nemes, P. Mafuka, E. Van Ranst, and W. Cornelis. 2013. Prediction of water retention of soils from the humid tropics by the nonparametric *k*-nearest neighbor approach. Vadose Zone J. 12(2). doi:10.2136/vzj2012.0123

Calonego, J.C., and C.A. Rosolem. 2011. Soil water retention and *S* index after crop rotation and chiseling. Rev. Bras. Cienc. Solo 35:1927–1937. doi:10.1590/S0100-06832011000600009

Cornelis, W.M., M. Khlosi, R. Hartmann, M. Van Meirvenne, and B. De Vos. 2005. Comparison of unimodal analytical expressions for the soil-water retention curve. Soil Sci. Soc. Am. J. 69:1902–1911. doi:10.2136/sssaj2004.0238

Cunha, E.Q., L.F. Stone, J.A. Alves Moreira, E.P. de Brito Ferreira, A.D. Didonet, and W.M. Leandro. 2011. Soil tillage systems and cover crops in organic production of common bean and corn: I. Soil physical properties. Rev. Bras. Cienc. Solo 35:589–602. doi:10.1590/S0100-06832011000200028

de Jong van Lier, Q. 2012. Indice S: Um indicador da qualidade fisica do solo? Bol. Inf. Soc. Bras. Cienc. Solo 37:24-27.

de Jong van Lier, Q. 2014. Revisiting the *S*-index for soil physical quality and its use in Brazil. Rev. Bras. Cienc. Solo 38:1–10. doi:10.1590/S0100-06832014000100001

Dexter, A.R. 1988. Advances in characterization of soil structure. Soil Tillage Res. 11:199–238. doi:10.1016/0167-1987(88)90002-5

Dexter, A.R. 2004a. Soil physical quality: I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120:201–214. doi:10.1016/j.geoderma.2003.09.004

Dexter, A.R. 2004b. Soil physical quality: II. Friability, tillage, tilth and hard-setting. Geoderma 120:215–225. doi:10.1016/j.geoderma.2003.09.005

Dexter, A.R. 2004c. Soil physical quality: III. Unsaturated hydraulic conductivity and general conclusions about *S*-theory. Geoderma 120:227–239. doi:10.1016/j.geoderma.2003.09.006

Dexter, A.R., and M. Birkas. 2004. Prediction of the soil structures produced by tillage. Soil Tillage Res. 79:233–238. doi:10.1016/j.still.2004.07.011

Dexter, A.R., and E.A. Czyż. 2007. Applications of *S*-theory in the study of soil physical degradation and its consequences. Land Degrad. Dev. 18:369–381. doi:10.1002/ldr.779

Dexter, A.R., E.A. Czyż, G. Richard, and A. Reszkowska. 2008. A user-friendly water retention function that takes account of the textural and structural pore spaces in soil. Geoderma 143:243–253. doi:10.1016/j.geoderma.2007.11.010

FAO. 2006. Guidelines for soil description. 4th ed. FAO, Rome. ftp://ftp.fao.org/agl/agll/docs/guidel_soil_descr.pdf (accessed December 2012).

Garg, R.N., S.P. Mazumdar, S. Chattaraj, D. Chakraborty, R. Singh, M. Kumari, et al. 2009. Assessment of soil physical conditions: Evaluation of a single value index. J. Agric. Phys. 9:9–19.

Gee, G.W., and D. Or. 2002. Particle-size analysis. In: J.H. Dane and G.C. Topp, editors, Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI. p. 255–293. doi:10.2136/sssabookser5.4.c12

Gilabert, J., I. López de Rojas, and R. Pérez de Roberti. 1990. Manual de métodos y procedimientos de referencia. Análisis de suelos para diagnóstico de fertilidad. Versión preliminar. Centro Nacional de Investigaciones Agropecuarias, Maracay, Venezuela.

Guimarães, R.M.L., B.C. Ball, and C.A. Tormena. 2011. Improvements in the visual evaluation of soil structure. Soil Use Manage. 27:395–403.

Kechavarzi, C., Q. Dawson, and P.B. Leeds-Harrison. 2010. Physical properties of low-lying agricultural peat soils in England. Geoderma 154:196–202. doi:10.1016/j.geoderma.2009.08.018

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. In: A. Klute, editor, Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. SSSA Book Ser. 5. ASA and SSSA, Madison, WI. p. 425–442. doi:10.2136/sssabookser5.1.2ed.c17

Lal, R., and M.K. Shukla. 2004. Principles of soil physics. Marcel Dekker, New York.

Minasny, B., and A.E. Hartemink. 2011. Predicting soil properties in the tropics. Earth Sci. Rev. 106:52–62. doi:10.1016/j.earscirev.2011.01.005

Mueller, L., G. Shepherd, U. Schindler, B.C. Ball, L.J. Munkholm, V. Hennings, et al. 2013. Evaluation of soil structure in the framework of an overall soil quality rating. Soil Tillage Res. 127:74–84. doi:10.1016/j.still.2012.03.002

Newell-Price, J.P., M.J. Whittingham, B.J. Chambers, and S. Peel. 2013. Visual soil evaluation in relation to measured soil physical properties in a survey of grassland soil compaction in England and Wales. Soil Tillage Res. 127:65–73. doi:10.1016/j.still.2012.03.003

Nguyen, P.M., K. Van Le, and W.M. Cornelis. 2014. Using categorical soil structure information to improve soil water retention estimates of tropical delta soils. Soil Res. 52:443–452. doi:10.1071/SR13256

NRCS. 2003. Saturated hydraulic conductivity: Water movement concepts and class history. Soil Surv. Tech. Note 6. Natl. Soil Surv. Ctr., Lincoln, NE. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/home/?cid=nrcs142p2_053573 (accessed 8 Aug. 2013).

Pagliai, M., and N. Vignozzi. 2002. The soil pore system as an indicator of soil quality. Adv. GeoEcol. 35:69–80.

Pierce, F.J., W.E. Larson, R.H. Dowdy, and W.A.P. Graham. 1983. Productivity of soils assessing long-term changes due to erosion. J. Soil Water Conserv. 38:39–44.

Pieri, C.J.M.G. 1992. Fertility of soils: A future for farming in the West African savannah. Springer-Verlag, Berlin, Germany.

Pulido Moncada, M., D. Gabriels, and W. Cornelis. 2014a. Data-driven analysis of soil quality indicators using limited data. Geoderma 235–236:271–278. doi:10.1016/j.geoderma.2014.07.014

Pulido Moncada, M., D. Gabriels, W. Cornelis, and D. Lobo. 2013. Comparing aggregate stability tests for soil physical quality indicators. Land Degrad. Dev. doi:10.1002/ldr.2225

Pulido Moncada, M., L. Helwig Penning, L.C. Timm, D. Gabriels, and W.M. Cornelis. 2014b. Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. Soil Tillage Res. 140:20–28. doi:10.1016/j.still.2014.02.009

Reynolds, W.D., C.F. Drury, C.S. Tan, C.A. Fox, and X.M. Yang. 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma 152:252–263. doi:10.1016/j.geoderma.2009.06.009

Schultz, B.B. 1985. Levene's test for relative variation. Syst. Biol. 34:449–456. doi:10.1093/sysbio/34.4.449

Shepherd, G. 2009. Field guide for pastoral grazing and cropping on flat to rolling country. Vol. 1. Visual soil assessment. 2nd ed. Horizons Regional Council, Palmerston North, New Zealand.

Silva Guedes, E.M., A.R. Fernandes, H.V. de Lima, A.P. Serra, J.R. Costa, and R.S. Guedes. 2012. Impacts of different management systems on the physical quality of an Amazonian Oxisol. Rev. Bras. Cienc. Solo 36:1269–1277. doi:10.1590/S0100-06832012000400021

Soil Survey Staff. 2010. Keys to soil taxonomy. 11th ed. NRCS, Washington, DC.

Tormena, C.A., Á. Pires da Silva, S. Del Carmen Imhoff, and A.R. Dexter. 2008. Quantification of the soil physical quality of a tropical Oxisol using the *S* index. Sci. Agric. 65:56–60. doi:10.1590/S0103-90162008000100008

van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898. doi:10.2136/sssaj1980.03615995004400050002x

Vanongeval, L., J. Bries, J. Meykens, W. Boon, H. Vandendriessche, and M. Geypens. 2000. The chemical soil fertility of the Belgian cropland and pasture areas (1996–1999). (In Dutch.) Bodemkundige Dienst van België, Heverlee, Belgium.

Vizitiu, O.P., I. Calciu, I. Pănoiu, and C. Simota. 2011. Soil physical quality as quantified by *S* index and hidrophysical indices of some soils from Argeş hydrographic basin. Res. J. Agric. Sci. 43:249–256.

Walkley, A., and I.A. Black. 1934. An examination of the Degtjareff method for determining organic carbon in soils: Effect of variations in digestion conditions and of inorganic soil constituents. Soil Sci. 63:251–263. doi:10.1097/00010694-194704000-00001

Fig. 1. (a) The soil water release curve and (b) the normalized pore volume distribution of the group of soils with good, moderate, and poor soil physical quality (SPQ).

Table 1. Description and characteristics of the medium-textured tropical (V2–V6 from Venezuela) and temperate (B1–B4 from Belgium) soils.

Site	Geographic coordinates	Textural class	USDA taxonomic class†	Soil use and management	Clay	Silt	Sand	pH_{KCl}
						g kg^{-1}		
V2	10°15′ N, 67°37′ W	clay loam	Fluventic Haplustoll	grazing, no-till, no trampling	291.0	282.3	426.7	7.67
V3	10°21′ N, 68°39′ W	loam	Typic Endoaqualf	maize monocropping, conventional tillage	172.8	350.7	476.5	4.90
V4	8°46′ N, 67°45′ W	loam	Aquic Haplustoll	grazing, no-till, permanent cattle	229.5	485.8	284.7	5.19
V5	9°0′ N, 67°41′ W	silt loam	Typic Rhodustalf	cereal crops with fallow periods, conventional tillage	261.0	583.0	156.0	4.84
V6	9°2′ N, 67°41′ W	silty clay	Aquic Haplustalf	grazing with natural vegetation, trampling	423.1	501.3	75.6	4.67
B1	50°59′ N, 3°31′ E	sandy loam	Inceptisol	cereal monocropping, conventional tillage	136.5	119.6	743.9	5.96
B2	50°46′ N, 3°35′ E	silt loam	Alfisol	cereal mono-cropping, conventional tillage	164.5	627.9	207.6	6.76
B3	50°47′ N, 3°25′ E	silt loam	Alfisol	corn–winter wheat rotation, conventional tillage	125.4	657.7	216.9	6.22
B4	50°47′ N, 2°49′ E	loam	Inceptisol	cereal–pasture rotation, reduce tillage, no trampling	97.7	531.8	370.5	6.52

† Soil Survey Staff (2010).

Table 2. Critical limits of the soil physical quality indicators.

Indicator	Critical limits	Reference
S index	≥0.050 and 0.050–0.035, very good and good soil physical quality <0.035, poor soil physical quality <0.020, very poor soil physical quality	Dexter and Czyż (2007)
Bulk density Mg m^{-3}	1.33, lower limit for soil compaction (medium-textured soils) 1.48, upper limit for soil compaction (medium-textured soils)	Pierce et al. (1983)
Air capacity, m^{3} m^{-3}	>0.10, adequate root zone aeration in sandy loam to clay loam soils	Reynolds et al. (2009)
Plant-available water capacity, m^{3} m^{-3}	≥0.15, good for root growth and function 0.10–0.15, limited for root growth and function <0.10, poor for root growth and function	Reynolds et al. (2009)

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Relative water capacity, $m^3\ m^{-3}$	0.6–0.7, optimal range required for good crop production	Reynolds et al. (2009)
Soil organic C, $g\ kg^{-1}$	Venezuelan soils medium-textured soils: <11.6, low 11.6–23.2, medium >23.2, high for fine-textured soils: <17.4, low 17.4–29, medium >29, high	Gilabert et al. (1990)
	Belgian soils (medium-textured) <12, low 12–16, target zone >16, high	Vanongeval et al. (2000
Structural stability index, %	<5, structurally degraded soil 5–7, high risk of structural degradation >9, sufficient soil organic C to maintain structural stability	Reynolds et al. (2009)
Saturated hydraulic conductivity, $cm\ h^{-1}$	18–1.8, optimal range required for water movement <1.8, very low water movement	NRCS (2003)
Water-stable aggregates, %	>70, high aggregate stability <50, low aggregate stability	Pulido Moncada et al. (2
Visual evaluation of soil structure	1–2, acceptable soil structure 3, moderate soil structure 4–5, limiting soil structure; requires change in management	Ball et al. (2007)
Visual soil assessment (VSA)	<20, poor soil quality >37, good soil quality	Shepherd (2009)
Soil structure indicator of the VSA protocol	0, poor soil quality 1, moderate soil quality 2, good soil quality	Shepherd (2009)
Visual type of aggregates index	1–2, good and moderately good structural quality 3, moderate structural quality 4–5, moderately poor and poor structural quality	Pulido Moncada et al. (2

Table 3. Mean values of the *S* index together with the van Genuchten (1980) parameters used in its calculation for the tropical soils from Venezuela (V2–V6) and temperate soils from Belgium (B1–B4). The values of θ_s, α, and *n* were calculated using the constraint $m = 1 - 1/n$ and the residual water content was fitted to zero.

Parameter†	V2	V3	V4	V5	V6	B1	B2	B3	B4
θ_s, $kg\ kg^{-1}$	0.4113	0.2547	0.3577	0.2401	0.3206	0.3909	0.3175	0.2968	0.2788
α, cm^{-1}	0.2316	0.0271	0.0124	0.0138	0.0305	0.0324	0.0158	0.0266	0.0088
n	1.1606	1.1892	1.2057	1.1483	1.1057	1.2999	1.2065	1.2128	1.2643
S	0.0454	0.0302	0.0445	0.0235	0.0243	0.0648	0.0405	0.0385	0.0421

† θ_s, water content at saturation; α and *n*, parameters related to the matric potential and the curve's slope at its inflection point, respectively; *S*, slope of the water retention curve at its inflection point.

Table 4. Global comparison of indicators and indices of soil physical quality (SPQ) for tropical soils from Venezuela (V2–V6) and temperate soils from Belgium (B1–B4), including bulk density (BD), air capacity (AC), plant-available water capacity (PAWC), relative water capacity (RWC), soil organic C (SOC), structural stability index (StI), saturated hydraulic conductivity (K_s), water-stable aggregates (WSA), visual evaluation of soil structure (VESS), visual soil assessment (VSA), soil structure indicator of the VSA protocol (SS_VSA), type of aggregate score (Tyagg), and the *S* index (the slope of the water retention curve at its inflection point). See Table 2 for critical limits of indicators.

Soil†	BD	AC	PAWC	RWC	SOC	StI	K_s	WSA	VESS	VSA	SS_VS

	Mg m^{-3}	— m^3 m^{-3} —			g kg^{-1}	%	cm h^{-1}	%			
							Good SPQ				
V2 clay loam, NT	1.37 good	0.11 good	0.15 good	0.74 aeration limited	24.4 high	7.3 low risk	25.97 rapid	82.2 good	2.0 intact	43.0 good	1.6 good
							Moderate SPQ				
V4 loam, NT, Tp	1.34 good	0.12 good	0.19 good	0.75 aeration limited	20.3 medium	4.9 degraded	0.76 medium	43.1 bad	3.3 firm	30.7 moderate	0.7 poor
V5 silt loam, CT	1.65 compacted	0.05 limited	0.13 limited	0.88 aeration limited	29.1 high	5.9 high risk	0.75 medium	93.4 good	3.5 firm/compact	28.2 moderate	1.0 moderate
B1 sandy loam, CT	1.33 good	0.27 good	0.19 good	0.46 water limited	11.1 mod-low	7.7 low risk	1.9 medium	44.9 bad	2.9 intact/firm	31.3 moderate	1.5 good
B2 silt loam, CT	1.44 moderate	0.15 good	0.16 good	0.68 good	13.4 ideal	2.9 degraded	0.06 very low	37.9 bad	3.7 firm/compact	23.6 moderate	0.9 moderate
B3 silt loam, CT	1.53 compacted	0.16 good	0.15 good	0.64 good	9.4 low	2.0 degraded	18.9 rapid	34.5 bad	3.1 firm	34.8 moderate	1.4 good
B4 loam, RT	1.46 moderate	0.16 good	0.18 good	0.66 good	9.6 low	2.6 degraded	0.36 medium	39.6 bad	2.6 intact/firm	40.1 good	1.4 good
							Poor SPQ				
V3 loam, CT	1.55 compacted	0.14 good	0.15 good	0.68 ideal	7.5 low	2.5 degraded	0.88 medium	37.1 bad	4.2 compact	14.9 poor	0.0 poor
V6 silty clay, NT, Tp	1.53 compacted	0.05 limited	0.12 limited	0.92 aeration limited	16.1 medium	2.9 degraded	1.81 medium	57.3 moderate	4.4 compact	11.0 poor	0.3 poor

† NT, no-till; Tp, trampling by cows; CT, conventional tillage; RT, reduced tillage.

Table 5. The relationships between the *S* index and other soil physical quality (SPQ) indicators and the estimation of *S* index critical values of using other SPQ indicators' critical values (*n* = 54).

Linear model†	R^2	*P* value	Critical limits of the predictor variable	Estimated critical values of *S*‡
$S = -0.893(BD) - 0.132$	0.54	0.00	1.33 Mg m^{-3} (lower limit) 1.48 Mg m^{-3} (upper limit)	0.047 0.035
$S = 1.678(AC) - 1.678$	0.60	0.00	>0.10 m^3 m^{-3} (optimal value)	>0.030
$S = -0.764(RWC) - 0.898$	0.60	0.00	0.6–0.7 m^3 m^{-3} (optimal value)	0.044- 0.036
$S = 0.001(K_s) - 1.465$	0.25	0.01	18–1.8 cm h^{-1} (optimal range)	0.035–0.034
$S = -0.054(VESS) - 1.266$	0.14	0.01	1–2 (acceptable soil structure) 3 (moderate soil structure) 4–5 (limiting soil structure)	0.047–0.042 0.037 0.032–0.029
$S = 0.005(VSA) - 1.595$	0.15	0.01	<20 (poor soil quality) >37 (good soil quality)	0.032 0.039

† Predictor variables are bulk density (BD), air capacity (AC), relative water capacity (RWC), saturated hydraulic conductivity (K_s), visual evaluation of soil structure (VESS), and visual soil assessment (VSA).

‡ *S* values estimated using the models given in the first column and the critical limits of the predictor variables. According to Dexter and Czyż (2007), $S \geq 0.050$ and 0.050–0.035 indicate very good and good SPQ, <0.035 indicates poor SPQ, and <0.020 indicates very poor SPQ.

Table 6. Location and shape parameters for the pore volume distributions of the tropical soils from Venezuela (V2–V6) and temperate soils from Belgium (B1–B4) categorized as good, moderate or poor soil physical quality (SPQ).

	Location parameters			Shape parameters	
Soil†	d_{mean}	d_{median}	d_{mode}	**Skewness**	**Kurtosis**
Good SPQ					
V2, clay loam, NT	2.80	9.27	125.60	−0.41	1.14
Moderate SPQ					
V4, loam, NT, Tp	0.53	1.30	8.59	−0.38	1.15
V5, silt loam, CT	0.11	0.39	6.97	−0.42	1.14
B1, sandy loam, CT	5.73	9.96	31.26	−0.34	1.16
B2, silt loam, CT	0.69	1.67	10.93	−0.38	1.15
B3, silt loam, CT	1.32	3.11	18.93	−0.38	1.15
B4, loam, RT	1.02	1.96	7.62	−0.35	1.15
Poor SPQ					
V3, loam, CT	0.78	2.10	17.24	−0.39	1.15
V6, silty clay, NT, Tp	0.02	0.13	10.90	−0.44	1.12

† NT, no till; Tp, trampling by cows; CT, conventional tillage; RT, reduced tillage.

Table 7. Water content (θ_i), modulus of the water potential (h_i), and equivalent pore diameter (d_i) at the inflection point of the water retention curve and the water content at field capacity (θ_{-33kPa}) for tropical soils from Venezuela (V2–V6) and temperate soils from Belgium (B1–B4) categorized as good, moderate or poor soil physical quality (SPQ).

Soil	θ_i	h_i	d_i	θ_{-33kPa}
	kg kg^{-1}	cm	µm	kg kg^{-1}
		Good SPQ		
V2	0.31	23.73	126.44	0.26
		Moderate SPQ		
V4	0.26	346.73	8.65	0.28
V5	0.18	427.66	7.01	0.20
B1	0.27	95.32	31.47	0.17
B2	0.23	272.64	11.00	0.22
B3	0.21	157.40	19.06	0.19
B4	0.19	391.29	7.67	0.20
		Poor SPQ		
V3	0.19	172.88	17.35	0.18
V6	0.25	273.47	10.97	0.25

Table 8. Statistics of the soil physical quality indicators evaluated.

Indicator†	***n***	**Min.**	**Max.**	**Mean**	**SE**	**SD**	**Levene's test‡ for CV**
BD, Mg m^{-3}	54	1.26	1.70	1.46	0.0162	0.1193	0.0731 a§
AC, m^3 m^{-3}	54	0.015	0.305	0.14	0.0091	0.0665	0.475 a
RWC, g kg^{-1}	54	0.42	1.03	0.71	0.0196	0.1440	0.1533 a
StI, %	54	1.85	9.15	4.34	0.3109	2.2850	0.4261 a
K_s, cm h^{-1}	54	0.02	220.77	20.93	6.5579	48.1904	1.2165 b
VESS	54	2.00	5.00	3.25	0.1139	0.8370	0.2232 a
VSA	54	6.50	45.50	28.61	1.4126	10.3803	0.2786 a
SS_VSA	54	0.00	2.00	1.09	0.1041	0.7652	0.4722 a
Tyagg	54	2.00	5.00	3.21	0.1235	0.9073	0.2661 a
S	54	0.0175	0.1047	0.0394	0.0022	0.0158	0.2896 a

† BD, bulk density; AC, air capacity; RWC, relative water capacity; SOC, soil organic C; StI, structural stability index; K_s, saturated hydraulic conductivity; VESS, visual evaluation of soil structure; VSA, visual soil assessment; SS_VSA, soil structure indicator of the VSA protocol; Tyagg, type of aggregate score; *S* , slope of the water retention curve at its inflection point.

‡ Schultz (1985).

§